

Capturing Relic Neutrinos with β -decaying Nuclei

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Abstract. We summarize a novel approach which has been recently proposed for direct detection of low energy neutrino backgrounds such as the cosmological relic neutrinos, exploiting neutrino/antineutrino capture on nuclei that spontaneously undergo β decay.

1. Introduction

The electron Neutrino Capture from a nucleus A which spontaneously decays via Beta decay to a daughter nucleus B (in the following NCB)

$$\bar{\nu}_e + A \rightarrow B + e^{\pm}, \quad (1)$$

shows the remarkable property that it has no energy threshold on the value of the incoming neutrino energy. In the limit of vanishing value for neutrino mass m_ν and energy the neutrino contributes to (1) uniquely via its lepton flavor quantum number and in this case the electron in the final state has exactly the β decay endpoint energy Q_β . However, for finite m_ν the electron kinetic energy is $Q_\beta + E_\nu \geq Q_\beta + m_\nu$, while electrons emerging from the corresponding β decay has at most an energy $Q_\beta - m_\nu$, neglecting nucleus recoil energy.

The idea of using NCB to measure the cosmological relic neutrino background predicted in the framework of the Hot Big Bang model was already suggested many years ago in [2]. The original idea was that if relic neutrinos have a large chemical potential μ , the electron (positron) energy spectrum for β decays and NCB would get quite a typical signature in a interval of order μ around the zero neutrino mass endpoint Q_β . However, Big Bang Nucleosynthesis constrains relic neutrino-antineutrino asymmetry to the small value $\mu/T_\nu \leq 0.1$, see e.g. [3, 4]. This implies that, unless more exotic scenarios are considered, as a larger amount of relativistic degrees of freedom in the Early Universe, the effect of neutrino degeneracy in β decays and NCB is too small to be detected experimentally. However, for massive neutrinos a gap around Q_β is expected of the order of twice the neutrino mass, which for $m_\nu \sim 1$ eV is several orders of magnitude larger than the corresponding effect due to neutrino-antineutrino asymmetry. At least in principle, this allows to distinguish between β decay and NCB interaction. In this paper we briefly summarize the results of [1] where it is argued that if m_ν is in the eV range, future NCB experiments could represent an almost unique way to detect cosmological neutrinos.

2. The Neutrino Capture Rate

Assuming an isotropic neutrino flux corresponding to a distribution function in phase space $f(p_\nu)$, the NCB integrated rate can be expressed as an integral over the electron (positron) energy

$$\lambda_\nu = \int \sigma_{\text{NCB}} v_\nu f(p_\nu) \frac{d^3 p_\nu}{(2\pi)^3} = \frac{G_\beta^2}{2\pi^3} \int_{W_o+2m_\nu}^\infty p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu E_\nu p_\nu f(p_\nu) dE_e, \quad (2)$$

where $F(Z, E_e)$ is the Fermi function, with E_e and p_e the energy and momentum of the outgoing electron and W_o the corresponding β decay endpoint. The rate contains the nuclear shape factor $C(E_e, p_\nu)_\nu$, an angular momentum weighted average of nuclear state transition amplitudes, which depends upon the nuclear properties of the parent and daughter nuclei and represents the main source of uncertainty in $\sigma_{\text{NCB}} v_\nu$, the product of the cross section times neutrino velocity.

On the other hand, NCB rate is strongly related to the corresponding β decay process rate

$$\lambda_\beta = \frac{G_\beta^2}{2\pi^3} \int_{m_e}^{W_o} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\beta E_\nu p_\nu dE_e, \quad (3)$$

where a simple relation between the two shape factors holds

$$C(E_e, p_\nu)_\nu = C(E_e, -p_\nu)_\beta, \quad (4)$$

though both variables have different kinematical domains in the two processes.

Therefore, the β decay rate can be used to provide a relation giving the mean shape factor, defined as

$$\overline{C}_\beta = \frac{1}{f} \int_{m_e}^{W_o} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\beta E_\nu p_\nu dE_e, \quad (5)$$

in terms of observable quantities, W_o and the product $ft_{1/2}$

$$ft_{1/2} = \frac{2\pi^3 \ln 2}{G_\beta^2 \overline{C}_\beta}, \quad (6)$$

Defining

$$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E'_e, p'_\nu)_\beta}{C(E_e, p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e, Z)}{F(E_e, Z)} E'_\nu p'_\nu dE'_e, \quad (7)$$

where a prime denotes all variables depending on E'_e which should be integrated over, the NCB cross section times neutrino velocity can then be conveniently written as

$$\sigma_{\text{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A} \cdot t_{1/2}}, \quad (8)$$

Notice that \mathcal{A} contains the ratio of NCB and β decay shape factors. As discussed in details in [1], in several relevant cases (super-allowed transitions, unique k-th forbidden transitions) the evaluation of \mathcal{A} is particularly simple so that Eq. (8) can be computed in an exact way. Furthermore, in all cases where this is not possible, systematic uncertainties affecting the nuclear matrix element evaluation largely cancel in the shape factor ratio appearing in \mathcal{A} , thus providing a reliable estimate of the NCB cross sections. Results for both allowed and unique forbidden decay cross sections having branching ratios greater than 5%, namely 1272 β^- decays and 799 β^+ decays can be found in [1]. Indeed, there are several nuclei spanning a wide range in Q_β for which interesting high values are reached in the range $\sigma_{\text{NCB}}(v_\nu/c) = 10^{-41} - 10^{-43} \text{ cm}^2$. As an example, in the interesting case of ^3H one gets $\sigma_{\text{NCB}}(v_\nu/c) = 7.84 \times 10^{-45} \text{ cm}^2$, which for

the standard homogeneous flux of cosmological neutrinos corresponds to 7.5 events per year of data taking for a mass of 100 g. In general, this estimate represents a lower bound, as massive neutrino density is expected to be locally larger because of gravitational clustering. This effect in a Cold Dark Matter Halo is quite relevant for order eV neutrino masses, see Table 1.

Of course, the finite energy resolution of any experimental apparatus and the extremely low cross section make relic neutrino detection via NCB a real challenge due to the large background events produced by standard β decay. In particular, the ratio of the event rate $\lambda_\beta(\Delta)$ for the last β decay electron energy bin $W_o - \Delta < E_e < W_o$, compared with the total NCB event rate is typically very large, since $\Delta \gg T_\nu$

$$\frac{\lambda_\beta(\Delta)}{\lambda_\nu} = \frac{2}{9\zeta(3)} \left(\frac{\Delta}{T_\nu}\right)^3 \left(1 + \frac{2m_\nu}{\Delta}\right)^{3/2} \gg 1, \quad (9)$$

It is therefore a crucial issue to reach an energy resolution, the electron energy bin dimension of the apparatus Δ , smaller than m_ν . For example, the expected background electron events which are produced by β decay, yet having an energy which corresponds to the relic neutrino capture energy bin centered at $E_e = W_o + 2m_\nu$ are smaller than a factor three with respect to NCB processes if $\Delta = 0.2$ eV for $m_\nu = 0.7$ eV, while a smaller neutrino mass of 0.3 eV requires $\Delta = 0.1$ eV. Presently, to obtain such an energy resolution seems very demanding. Nevertheless, if a large neutrino mass will be found by the ongoing β decay experiment KATRIN [5], it is conceivable that more efforts could be devoted to future generation of experiments with an improved energy resolution as good as 0.1 eV.

Table 1. Relic neutrino capture rate for 100 g of ^3H , for a standard Fermi-Dirac distribution with $T_\nu = 1.7 \cdot 10^{-4}$ eV (FD). Results are also shown for a Navarro Frenk and White profile (NFW) and for present day mass distribution of the Milky Way (MW) for two values of m_ν .

m_ν (eV)	FD (events yr $^{-1}$)	NFW (events yr $^{-1}$)	MW (events yr $^{-1}$)
0.3	7.5	23	33
0.15	7.5	10	12

3. Conclusion

In this paper we have summarized the analysis of NCB performed in [1]. These processes have the remarkable property of having no energy threshold on the incoming neutrino energy and thus they might represent a good and numerous class of interactions suitable for low energy neutrino flux measurements. The possibility to pursue the ultimate goal of cosmological relic neutrino background detection via a future experimental implementation of this approach depends upon two crucial issues, a high value for the expected order of magnitude of NCB event rate, as well as a very good energy resolution of the outgoing electron or positron, of the order of neutrino mass. Both these aspects should be optimized by a careful choice of the β decaying nuclei.

References

- [1] Cocco A, Mangano G and Messina M 2007 *J. Cosmol. Astropart. Phys.* JCAP0706(2007)015
- [2] Weinberg S 1962 *Phys. Rev.* **128** 1457
- [3] Cuoco A *et al.* 2004 *Int. J. Mod Phys. A* **19** 4431
- [4] Hansen S H *et al.* 2002 *Phys. Rev. D* **65** 023511
- [5] Osipowicz A *et al.* [KATRIN Collaboration] 2001 arXiv:hep-ex/0109033
- [6] Ringwald A and Wong Y Y Y 2004 *J. Cosmol. Astropart. Phys.* JCAP0412(2004)005